Advanced Satellite-Derived Wind Observations, Assimilation, and Targeting Strategies during TCS-08 for Developing Improved Operational Analysis and Prediction of Western Pacific Tropical Cyclones

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LONG-TERM GOALS

Forecasts of tropical cyclone (TC) formation and intensity change in the north-western Pacific basin are often lacking in skill, in part due to the paucity of conventional oceanic observations that are assimilated into the operational models. This lack of observations has also constrained our understanding of how TC formation is governed by environmental processes. Recently, remotely-sensed observations from satellites have become a routine and important input to the global data assimilation systems. These data can provide critical environmental data for the testing of hypotheses of TC formation and development, and improving our understanding of how environmental influences on TC structure evolve up to landfall or extratropical transition. In particular, winds derived from geostationary satellites have been shown to be an important component of the observing system in reducing TC model track forecasts. However, in regards to TC formation, intensity change, and extratropical transition, it is clear that a dedicated research effort is needed to optimize the satellite data processing strategies, assimilation, and applications to better understand the behavior of the near-storm environmental flow fields during these evolutionary TC stages. To our knowledge, this project represents the first time anyone has tried to evaluate the impact of targeted *satellite* data on TC forecasts using an automated dynamic targeted observing strategy. TCS-08 afforded us the opportunity to employ specially-processed satellite data along with observations collected in situ by the NAVY P-3, and other platforms, to investigate these objectives as they apply in the western north Pacific TC basin. The development of successful real-time strategies to optimally assimilate wind data from

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satellites will ultimately lead to the provision of improved initial and boundary conditions for the Navy's envisioned mesoscale coupled ocean-wave-atmosphere forecast model.

OBJECTIVES

The ultimate objective of this project is the development and refinement of a capability to supplement the contemporary atmospheric observation network with advanced satellite wind observations to improve high-resolution operational analyses and medium-range forecasts of western North Pacific typhoons.

One primary research goal is to evaluate and diagnose the impact of assimilating the advanced satellite wind observations on global Navy model forecasts, and high-resolution forecasts of structure change. We aim to better understand how to utilize the satellite wind data in the context of numerical model assimilation and forecast impact. Optimizing the assimilation of the experimental satellite winds will involve a continued investigation of the satellite data impacts with respect to objective targeting of analysis-sensitive regions, and utilizing 4DVAR approaches.

APPROACH

During the field phase of TCS-08, experimental satellite-derived wind observations were produced by UW-CIMSS using state-of-the-art automated methods. Hourly datasets were routinely derived from operational images provided from the Japan Meteorological Agency (JMA) MTSAT geostationary satellite. In addition, special rapid-scan (r/s) images from MTSAT-2 were provided by JMA for extended periods (24-48hrs) over specific regions, and including parts of selected typhoon life cycles. UW-CIMSS also processed these images into wind fields (higher resolution). These special satellite-derived wind observations complemented those data collected by the NRL P-3 aircraft during TCS-08, by providing unique time-continuous environmental data in locations that were deemed important to tropical cyclone formation and development.

The project uses the latest versions of the NRL Atmospheric Variational Data Assimilation System – Accelerated Representer (NAVDAS-AR) and NOGAPS, the Navy's operational data assimilation and global forecast model systems during the period of our study, so that the research results may be easily transitioned to improve the Navy's operational predictions. We expect that the NAVDAS 4DVAR assimilation will provide an improved analysis, since its temporal continuity better exploits the asynoptic satellite winds than 3DVAR, in which the observations are assimilated at discrete 6-hour intervals.

Existing adaptive observing strategies such as the Ensemble Transform Kalman Filter (ETKF) and NOGAPS Singular Vectors have been used to identify regions in which numerical forecasts are most likely to benefit from the assimilation of additional satellite wind data. Via the observation sensitivity method (for forecasts up to 24h) and data denial in the Navy forecast system (for forecasts up to 5 days), the impact of assimilating targeted high-density (hourly and rapid-scan) satellite winds on global model forecasts of tropical cyclone track and high-resolution forecasts of tropical cyclone structure is being evaluated and analyzed.

Finally, a method to diagnose the effects of modifying the wind analysis on forecasts of tropical cyclone track has been designed. This framework, designed using the Weather Research and Forecasting (WRF) model, can be extended for use in the COAMPS-TC framework at the Naval Research Laboratory, Monterey, and can be used to diagnose the effects of environmental perturbations on tropical cyclone intensity and structure.

WORK COMPLETED THIS REPORTING PERIOD

i) University of Wisconsin-CIMSS, in collaboration with NRL-MRY

In the final year of this funded study, the UW-CIMSS team collaborated with scientists at NRL-MRY to finish up data impact studies using the specially processed AMV datasets (hourly and special rapid-scan) produced from MTSAT by UW-CIMSS, as described in previous reports. A series of experiments to quantify the impact of the MTSAT AMVs during TCS-08 using the operational version of the NAVDAS-AR concluded that the hourly AMVs, enhanced with the rapid-scan AMVs when available, contribute to a significant improvement in the NOGAPS forecasts of Western North Pacific tropical cyclones during the TCS-08 period. These findings were reported earlier (Berger et al., 2011), and have also resulted in operational implementation of hourly AMVs into the FNMOC NAVDAS system.

An experiment was performed in the NAVDAS-AR/NAVGEM to observe the impact of removing all UW-CIMSS AMV products from the input observation datastream. This was done to test the redundancy of AMV information in the Navy system, as AMVs are also supplied by AFWA, NESDIS, JMA and EUMETSAT. An insignificant impact would be interpreted as saying that there exists significant agency redundancy where AMVs are concerned. The experiment was carried out over the period 15 Aug – 30 Nov 2012, with 5-day forecasts performed on every six-hourly analysis cycle. In the experiment, all routinely-available operational AMVs from geostationary and polar satellites were supplied by national satellite operating agencies. UW-CIMSS also processes all of these satellite observations into AMV datasets on a regular basis for input into NAVDAS. In the control run, UW-CIMSS AMVs were allowed to be ingested as normal, relegating many of the other agency datasets to a "backup" position where they were only utilized if CIMSS winds were not available.

When UW-CIMSS AMVs are excluded, the 500 hPa geopotential height anomaly correlation scores degrade in both hemispheres (Fig. 1). Degradation is statistically significant at 24-48 hours in the northern hemisphere with statistically insignificant degradation through day-5. In the southern hemisphere, statistically significant degradation is observed at all forecast times. This underscores the importance of UW-CIMSS AMV products in the Navy data assimilation and forecast system, and makes it clear that there does not exist sufficient agency redundancy to overcome the potential loss of UW-CIMSS-provided AMV data.

Preliminary examination of TC track data from west Pacific typhoons present during the test period show that the UW-CIMSS AMVs tend to improve the forecast, with degraded track forecasts appearing in the data denial experiment (Fig. 2). The inclusion of UW-CIMSS AMVs also appears to have the effect of intensifying the TC forecasts through the 5-days, in general (not shown).

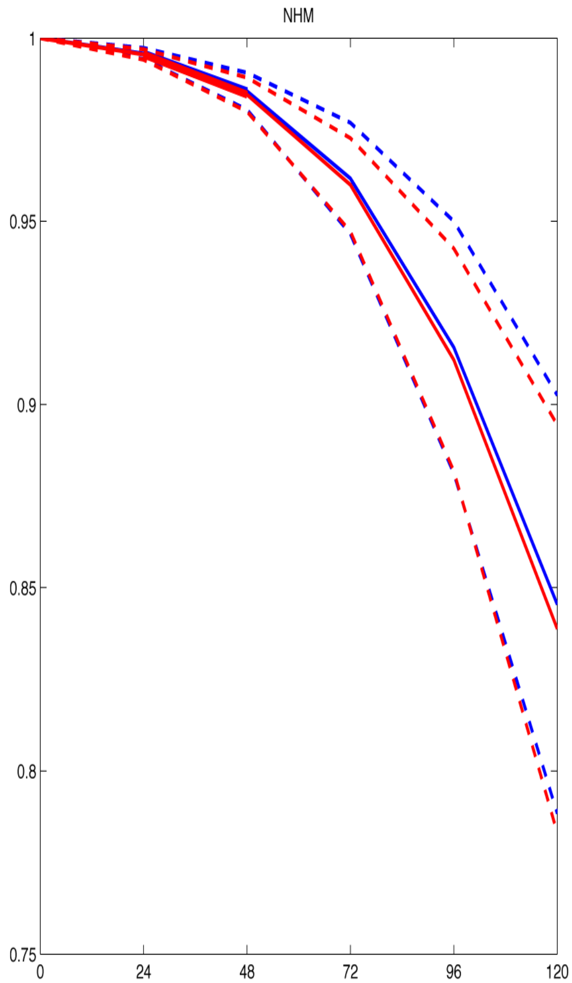

Figure 1. Average 500 hPa geopotential height anomaly correlation scores for the northern (left) and southern (right) hemispheres. The red (blue) solid line indicates the mean curve from day-0 to day-5 for the denial experiment (control), and the dashed lines represent one standard deviation from the mean. Statistically significant differences between the curves are represented by the solid lines being bold.

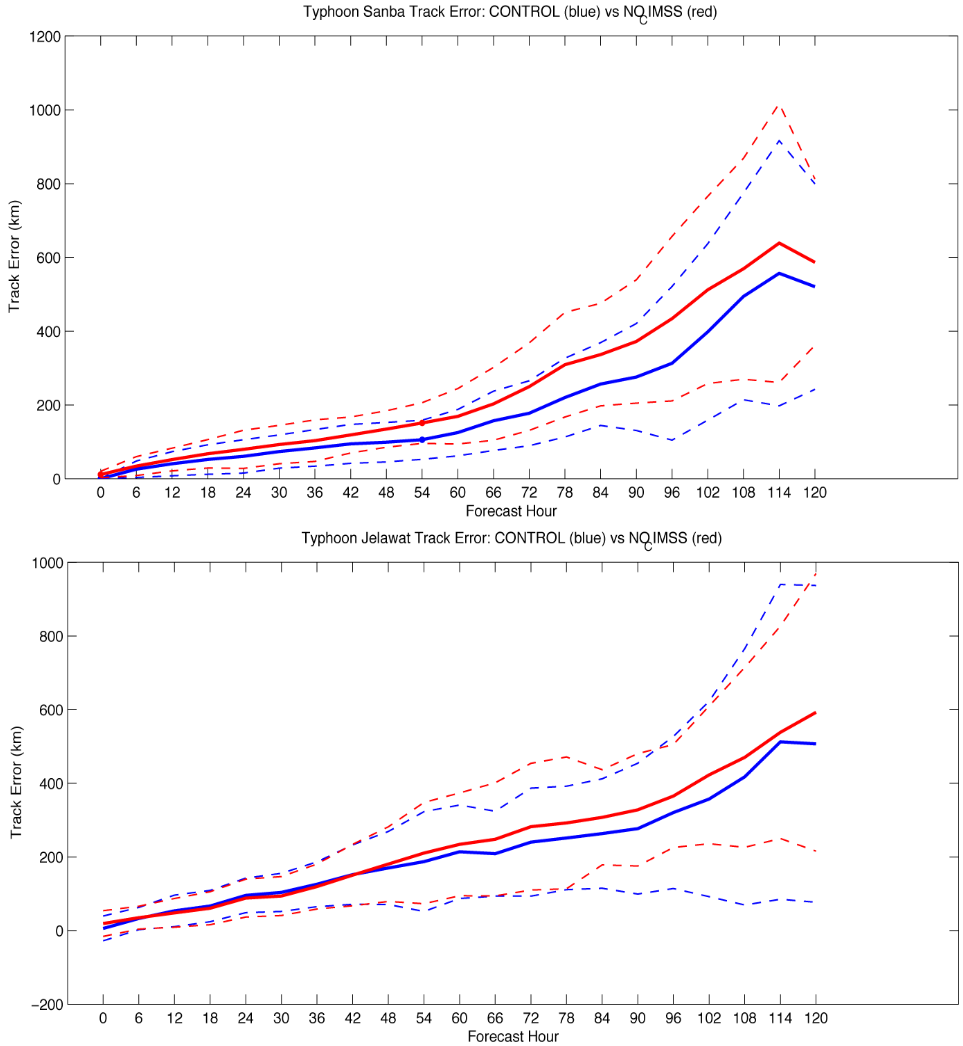

Figure 2. Average TC track error of Typhoon Sanba (top) and Typhoon Jelawat (bottom). The solid red (blue) line represents the mean track error of the denial experiment (control) through the 120-hr forecast. The dotted lines represent one standard deviation from the mean. Track error in km is computed from the observed location of the TC in the control analysis.

Further experiments suggest that a reformulation of the synthetic tropical cyclone observation scheme used in NOGAPS may lead to improved forecasts as more in-situ and remote observations become available, but the synthetic observations still appear to provide value at the current model resolution (Reynolds et al., 2013). These findings also illustrate how model biases may limit the potential improvements available through the assimilation of additional observations, and how this impact may vary substantially from storm to storm. The cause of this bias has not been established, but work is ongoing at NRL toward improving several aspects of the model formulation, including numerics, physical parameterizations, and increased horizontal resolution. The results obtained by increasing the assigned synthetic observation errors suggest that the formulation of the synthetic observations should be revisited as model resolution is increased and as more remote and in-situ observations are assimilated.

An experiment was performed in the NAVDAS-AR/NAVGEM system to assimilate profiles of zonal wind, meridional wind, and temperature from the European Center for Medium-Range Weather Forecasts (ECMWF) analysis as synthetic radiosonde observations. The purpose of this experiment was to: (1) observe the impact of these ECMWF pseudo-RAOBs on the NAVGEM analysis and subsequent forecast, in order to determine if deficiencies exist within the NAVGEM forecast that can be mitigated by incorporating ECMWF analysis information, (2) use the NAVDAS-AR calculation of observation-impact to observe the impact of ECMWF pseudo-RAOBs on the assimilation of other observation types within the system, and (3) to investigate the efficacy of using these profiles in an OSE framework to perform targeted-observation experiments to improve TC forecasting in the NAVGEM.

Profiles were derived from the ECMWF analysis at every $5^o x 5^o$ grid point between 85S – 85N, through eight standard pressure levels between 1000 hPa and 200 hPa. Profiles were given estimated errors similar to those given to regular radiosonde observations, and were ingested into the NAVDAS-AR in a similar fashion. ECMWF pseudo-RAOBs were created for every 0000 UTC and 1200 UTC analysis period between 20 August – 01 September 2012, covering a period with one TC in the Atlantic (Tropical Storm Isaac) and two TCs in the west Pacific (Typhoon Tembin and Super-Typhoon Bolaven). ECMWF pseudo-RAOBs were assimilated globally, as well as in regions demarcated by latitude – "polar" (65^o - 85^o), "midlatitude" (60^o - 35^o), and "tropical" (30S – 30N). Forecasts were performed on every six-hourly analysis out to 120 hours.

The impact of ECMWF pseudo-RAOBs on the 500 hPa geopotential height analysis is typified by an overall increase in the 500 hPa geopotential height gradient in the 30S – 60S corridor, with lower heights poleward of this region and slightly higher heights equatorward (Fig. 3). This impact is replicated in the polar and midlatitude (regional) assimilation experiments as well. It is speculated that this increase in the geopotential height gradient represents an increase in both baroclinic and barotropic energy at model initialization, which translates to increased wave-amplitudes in the mid-range forecast at day-5 (Fig. 4). The colocation of positive (negative) height perturbations with ridge (trough) axes in the southern hemispheric midlatitudes appears to be a signal representing increased wave-amplitudes at day-5. It is worth noting that anomalously low wave-amplitude in the mid-range forecast has been previously identified as a systemic forecast challenge in the NAVGEM (Langland, personal communication).

It is believed that the systemic impact of pseudo-RAOBs on the southern hemispheric polar region is largely due to the pseudo-RAOBs being able to address issues of model bias. This region relies heavily on radiance observations, which are adjusted to assume no model bias. The pseudo-RAOBs therefore act as an independent check on lower-tropospheric temperatures in this region, also affecting geopotential heights.

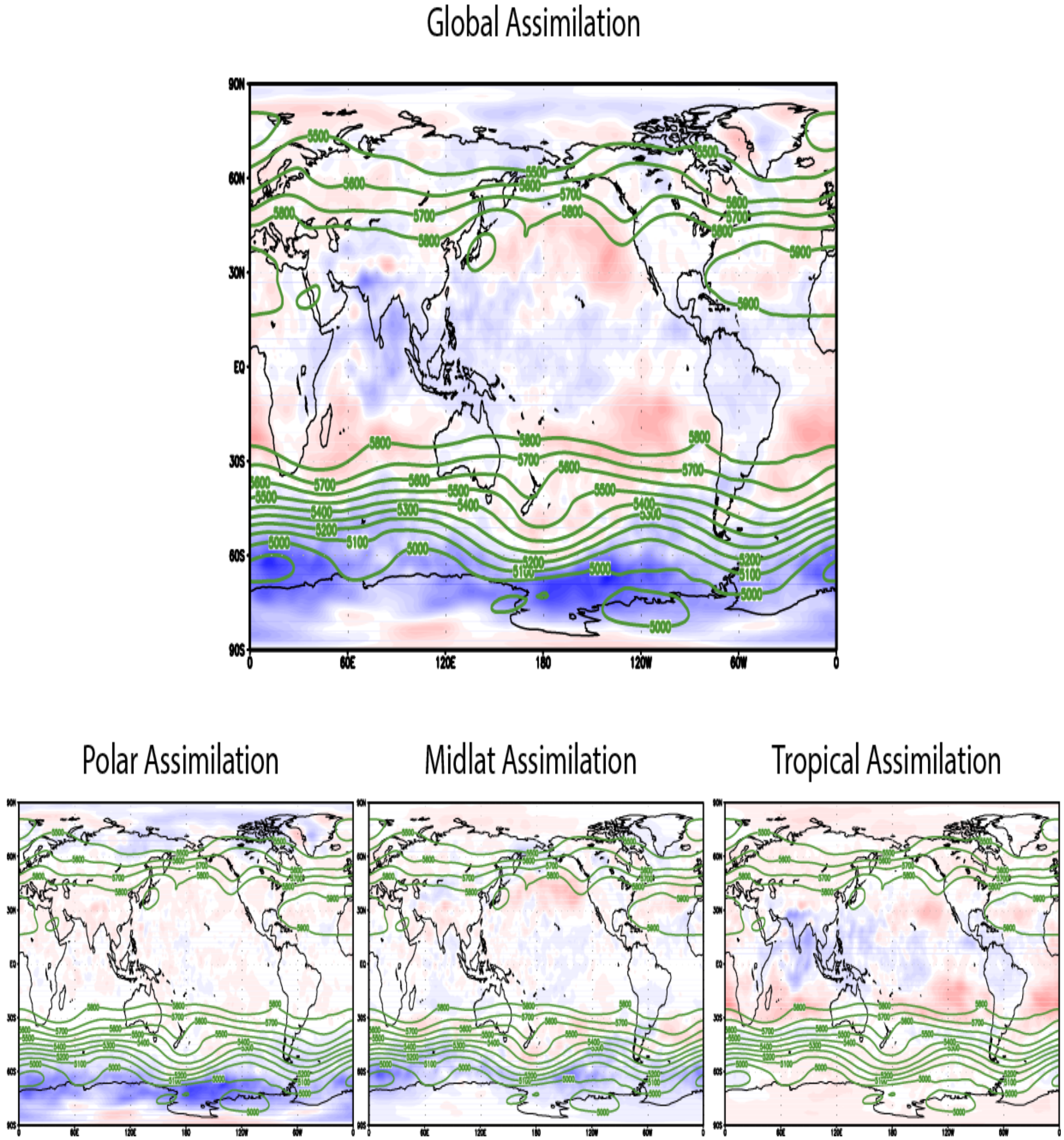

Figure 3. Difference between experiment and control 500 hPa analysis geopotential heights (shaded, cool colors negative) and control 500 hPa geopotential heights (green contours) averaged over all analysis periods between 0000 UTC Aug 20 – 1200 UTC Sep 01 2012. The top panel shows the difference between the global assimilation experiment and the control. The bottom three panels show the differences in the: (left) polar assimilation experiment, (middle) mid-latitude assimilation experiment, and (right) tropical assimilation experiment, and the control. Height differences range between -30 m and +5 m.

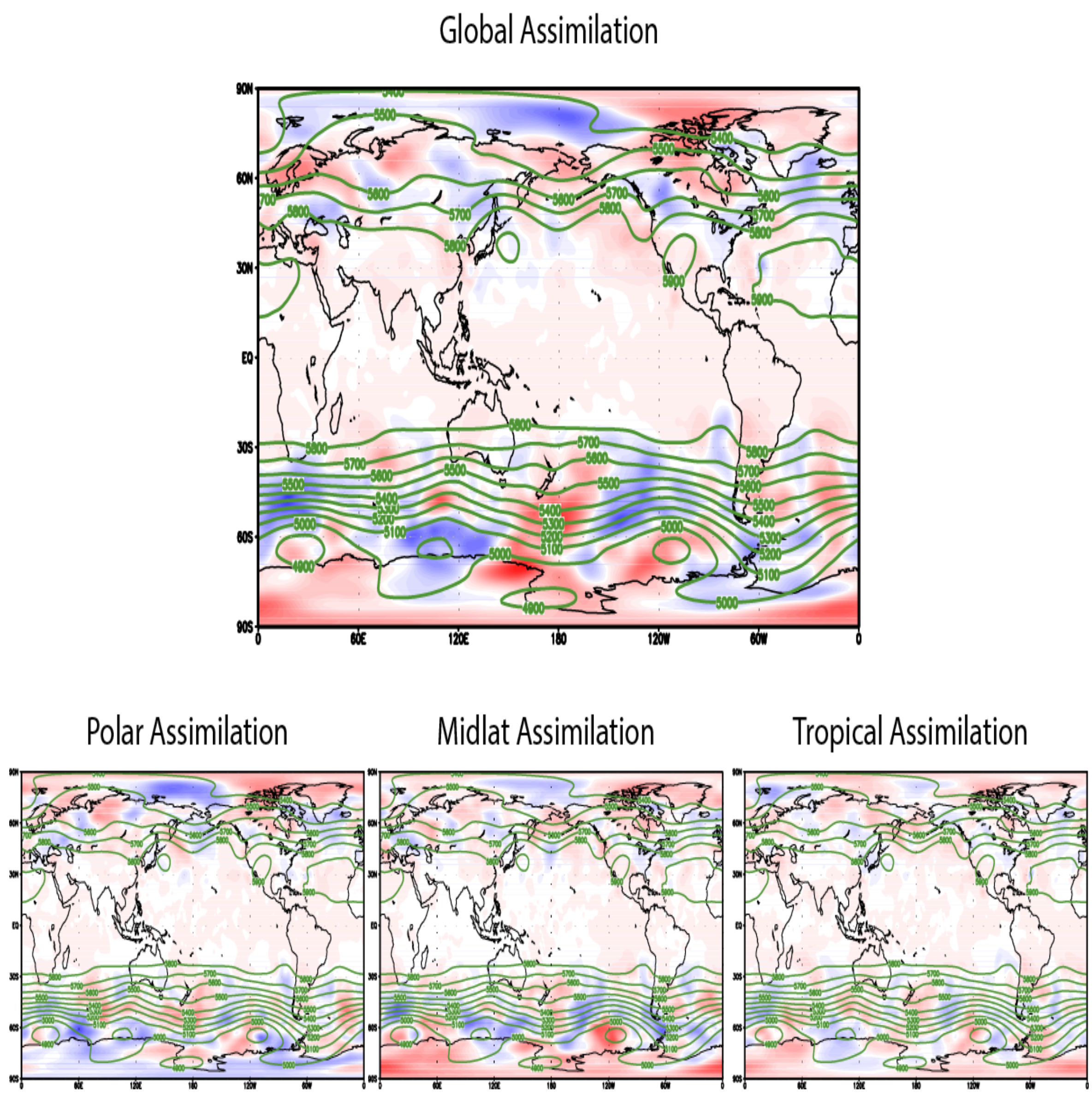

Figure 4. Difference between experiment and control 500 hPa day-5 forecast geopotential heights (shaded, cool colors negative) and control 500 hPa geopotential heights (green contours) averaged over all forecast periods between 0000 UTC Aug 21 – 1200 UTC Sep 01 2012. The top panel shows the difference between the global assimilation experiment and the control. The bottom three panels show the difference between the: (left) polar assimilation experiment, (middle) midlatitude assimilation experiment, and (right) tropical assimilation experiment, and the control. Height differences range between -40 m and +40 m.

Significant forecast improvement appears at all forecast times, with barely a single control forecast able to compete with the (global assimilation) experiment (Fig. 5). While forecast improvement appears across-the-board, as forecasts extend to mid-range, improvement starts to withdraw toward individual forecasts where the control performed poorly (forecast dropouts), while remaining closer to neutral otherwise.

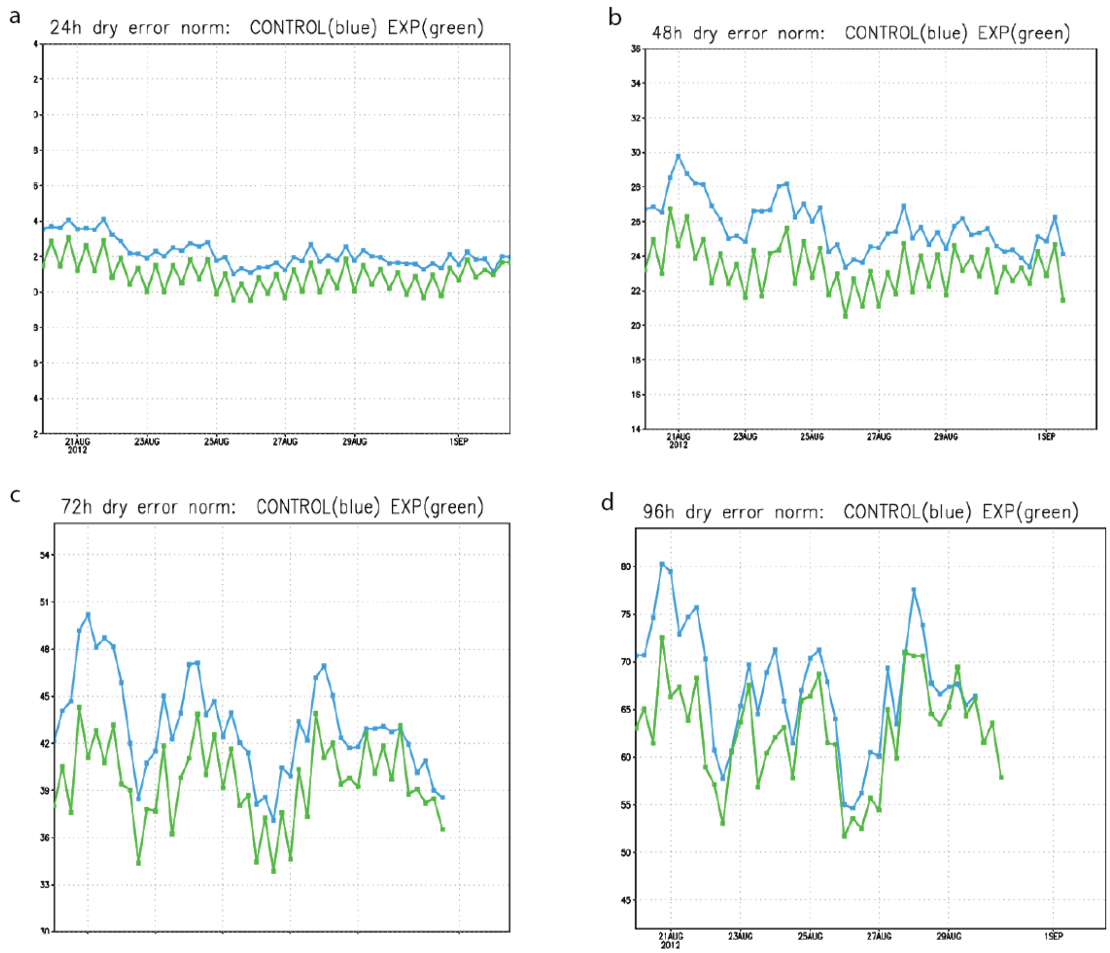

Figure 5. Global (dry) energy based error-norm (J kg^{-1}) for (a) 24-hr forecast, (b) 48-hr forecast, (c) 72-hr forecast, and (d) 96-hr forecast. The blue line represents the error of the control forecast, and the green line is the error of the forecast from the global assimilation experiment.

Forecast improvement from the assimilation of ECMWF pseudo-RAOBs accounts for a reduction in the energy based error-norm of between 10% (24-hr forecast) and 5% (120-hr forecast) on average, with reductions on individual forecast dropouts achieving values as high as 18%. The “saw-tooth” appearance to the error in the experiment is due to higher error in forecasts initialized at 0600 UTC and 1800 UTC, when no ECMWF pseudo-RAOBs were present. However, the information from pseudo-RAOBs in previous cycles, present in the analysis background state, still contributes to error reductions in the forecast that correspond to superior forecast performance relative to the control.

The adjoint-derived observation-impact of ECMWF pseudo-RAOBs is higher than any other observing platform in the system, with all other observing platforms experiencing a reduction in total observation-impact (Fig. 6). The loss of observation-impact from routine observations exceeds the gain in observation-impact from the pseudo-RAOBs themselves, meaning that the total observation-impact of the observing system is reduced when pseudo-RAOBs are assimilated. This represents a global improvement of the analysis/forecast system – as the analysis background state improves, observations

impose a smaller impact on the analysis and express smaller observation-impact on the 24-hr forecast state. A significant reduction in impact from AMVs, both from geostationary and polar-orbiting platforms, suggests that pseudo-RAOBs are correcting an existing imbalance in the control's analysis system. It is speculated that improper assimilation of radiance observations prevents these observations from addressing model biases, especially in the southern hemispheric polar latitudes, which causes the system to rely too heavily on wind information supplied by AMVs. The pseudo-RAOBs appear to provide a necessary check against mass field information in this region.

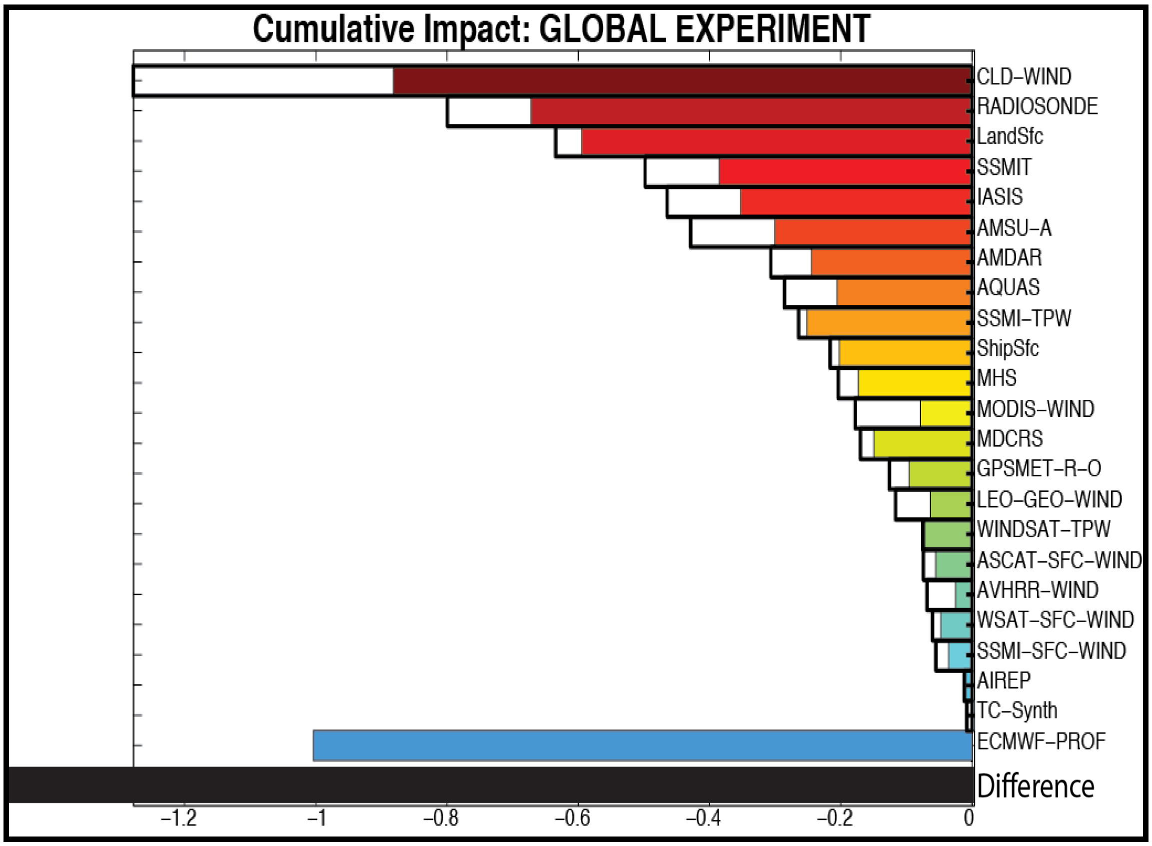

Figure 6. Adjoint-derived observation-impact from each observation platform (colored bars), representing the contribution of that platform to reducing the error in the 24-hr forecast. Each bar contains a black outline of the observation-impact of that same platform in the control; colored bars shorter than the outline are platforms that experience reduced observation-impact relative to the control. The impact from ECMWF pseudo-RAOBs is shown as the blue bar near the bottom of the figure. The black bar at the bottom represents the total loss of impact from all routine (non ECMWF pseudo-RAOB) observation platforms.

Impact of pseudo-RAOBs on TC tracks was insignificant (not shown), however, it is believed that the 5-degree resolution of the dataset is too coarse to be properly used for targeting purposes. A follow-on experiment using pseudo-raob data at 1 or 0.5 degree resolution is planned to examine in more detail these issues related to improvement of TC track forecasts.

ii) University of Miami

With the remaining final-year funds available, the stipend and tuition for Jason Godwin, a new M.S. student at the University of Miami, has been partially funded. The primary goal of Godwin's research is to investigate the sensitivity of TC structure to upper-tropospheric influences such as the interaction of mid-latitude shortwave troughs and TC outflow. This study continues in a similar vein to a previous study by Komaromi et al. (2011), which was also funded under this grant. Since that study, computational resources have expanded sufficiently to enable this new study to focus more on TC structure, while the constraints of model resolution had reduced the previous study to TC track.

The first TC selected for this study is Irene (2011), due to the abundance of available satellite and *in-situ* data, its importance to coastal operations in the northeastern United States, and a relative lack of research on this TC despite significant challenges faced in predicting its structure and intensity. The Weather Research and Forecasting (WRF) model with 9 km horizontal grid spacing and a large domain is being considered in order to test the sensitivity of simulations of Irene's internal structure to remote features in the synoptic environment. First, a WRF 'control' simulation was initialized at 0000 UTC 23 August 2011, as there were interesting challenges in the predictability of Irene at this time (Majumdar et al. 2013). Several upper-tropospheric shortwaves were present (Fig. 7a), and reasonably well-captured in the WRF forecast (Fig. 7b). The WRF track forecast of Irene was accurate (not shown), and the main intensification trend was captured adequately (Fig. 7c).

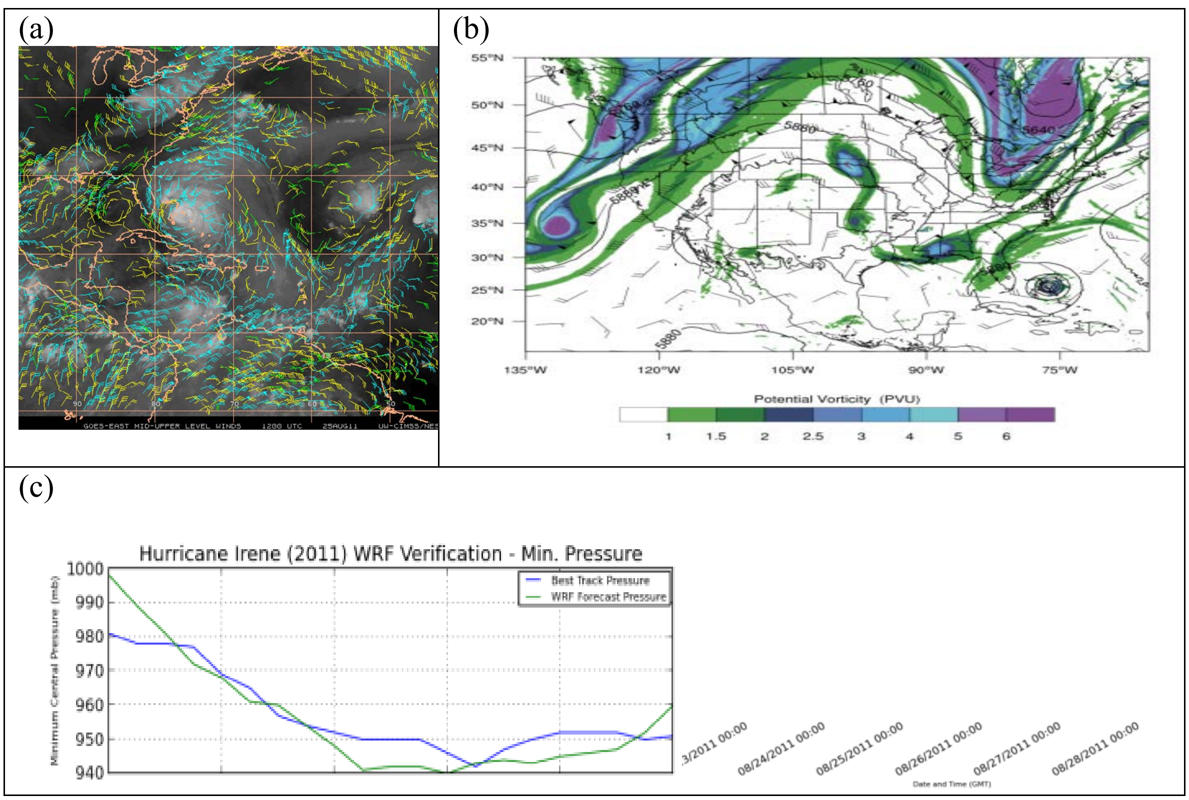

Figure 7. (a) CIMSS upper-layer winds on 1200 UTC 25 August 2011. (b) 250 hPa Potential Vorticity (shaded, in PVU), winds and 500 hPa geopotential height (contours), for a 60-h WRF simulation initialized at 0000 UTC 23 August 2011. (c) Comparison of the WRF forecast of the MSLP of Irene (green) with the Nat. Hurricane Center best track (blue).

The structure of Irene in the control simulation, including the surface winds, radar reflectivity and outgoing longwave radiation, is presently being evaluated (Fig. 8). Once this has been completed, perturbations to the environmental wind will be made using the software developed on this TCS-08 grant by Komaromi et al. (2011). The primary hypothesis is that two small upper-tropospheric shortwaves over the contiguous United States were significant controllers of the outflow and structure change of Irene prior to its landfalls on the Eastern Seaboard. This study will continue in 2014 under separate funding from the University of Miami.

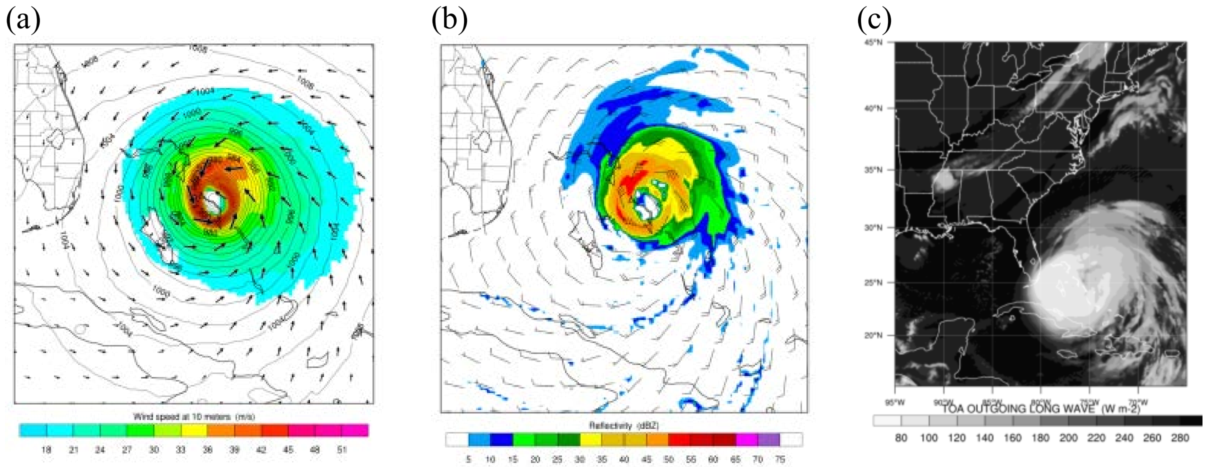

Figure 8. WRF 'Control' simulations of Hurricane Irene: (a) 10-m winds and sea level pressure; (b) 10-m winds and simulated radar reflectivity; and (c) simulated Outgoing Longwave Radiation (OLR)

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IMPACT/APPLICATIONS

A quantitative understanding of the influence of improved representations of the synoptic environment and outflow in the tropical cyclone will lead to new scientific conclusions on environmental interactions and modifications to tropical cyclone track and structure. The longer-term impact will be derived from the improved assimilation of targeted satellite wind observations in Navy (and other) models.

TRANSITIONS

As a result of this study, the assimilation of AMVs into the Navy's global assimilation and prediction system has benefited from findings and verification studies (OSEs). These benefits are now being realized in the FNMOC operational system.

RELATED PROJECTS

This project is related to that funded by the TCS-08 grant N000140810250: "Using NOGAPS Singular Vectors to Diagnose Large-Scales on Tropical Cyclogenesis" (PI Majumdar; Co-PIs Peng and Reynolds of NRL Monterey). A supplement to the budget on that grant has enabled the further development of the WRF vortex initialization and inversion software for easy use by students and collaborators. This software is also being tested in the NOPP collaboration between Velden and Majumdar cited below.

This project is also related to that funded by NOPP grant N00014-10-1-0123: "Achieving Superior Tropical Cyclone Intensity Forecasts by Improving the Assimilation of High-Resolution Satellite Data into Mesoscale Prediction Models" (PIs Velden and Majumdar, Co-PIs Doyle and Hawkins of NRL-MRY).

PUBLICATIONS

Hoover, B. T., C. S. Velden, and S. J. Majumdar, 2013: Physical Mechanisms Underlying Selected Adaptive Sampling Techniques for Tropical Cyclones. *Mon. Wea. Rev.* [in press].

Reynolds, C., R. Langland, P. Pauley, and C. Velden, 2013: Tropical Cyclone Data Impact Studies: Influence of Model Bias and Synthetic Observations. *Mon. Wea. Rev.* [in press].

HONORS/AWARDS/PRIZES

Co-PI Majumdar was assigned as Co-Chair of the American Meteorological Society's annual conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans and Land Surface (IOAS-AOLS), held at the AMS Annual Meeting.

Co-PI Majumdar was appointed Director of the Graduate Program in Meteorology and Physical Oceanography, and Chair of the School Graduate Academic Committee.

Co-PI Velden was awarded the 2012 University of Wisconsin Chancellor's Award for Distinguished Research.